Methane flux from created marshes: Effects of intermittent vs. continuous inundation and emergent macrophytes

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Introduction

Wetlands are the major natural source of the greenhouse gas methane (CH_4) due to the presence of anaerobic soil conditions that are necessary for methanogenesis (Le Mer and Roger, 2001). The majority of studies reporting on CH_4 emissions from wetlands have been conducted in natural ecosystems or heavily-managed rice paddies (Cao et al., 1998). Few publications exist that document CH_4 flux from created and restored wetlands (Schipper and Reddy, 1994; Tuittila et al., 2000). Because CH_4 has a global warming potential 23 times greater than that of carbon dioxide over a 100-year time horizon (IPCC, 2001) minimizing its emission from created and restored wetlands is a desirable goal.

Riparian wetland restoration and creation involves re-inundation of disconnected floodplain areas, often by partial removal of river bank levees, or by creating wetlands to intercept lateral runoff before it reaches the river. While productivity of wetlands has been shown to be enhanced by a seasonally pulsed flood regime (Mitsch and Ewel, 1979; Odum et al., 1995; Tockner and Stanford, 2002), macrophyte productivity has been positively correlated with methane emissions across a variety of natural wetland ecosystems with standing water (Whiting and Chanton, 1993; van der Nat and Middelburg, 2000; Hirota et al., 2004). Emergent macrophytes can transport gases via pressurized ventilation from sediments to the atmosphere (Brix et al., 1992), and simple diffusion through air-filled tissue (aerenchyma) in plant roots and stems. In addition, plant roots and detritus provide organic matter to sediment microbial communities that can be used for methanogenesis under anaerobic conditions (Schütz et al., 1991). When the water table is below the soil surface, however, the positive effect of macrophytes on CH_4 emission may be cancelled out by CH_4 oxidation (Waddington et al., 1996). The relationship between macrophytes and CH_4 flux remains poorly understood in wetlands with a highly variable water table.

The objectives of this study were to examine and compare the effects of intermittent vs. continuous inundation, and emergent macrophytes on methane flux from multiple sites in the two 1-ha, experimental marshes at the Olentangy River Wetland Research Park (ORWRP). The central third of each wetland is a deeper water area that has been consistently inundated for ten years, while the outer two thirds of each wetland are shallower and generally support growth of emergent macrophytes.

Materials and Methods

Hydrology

Pulsing hydrologic conditions were created during 2004 (Figure 1), designed to simulate a hydroperiod typical of riparian wetlands receiving floodwaters in winter and spring, with a drier period during summer and fall. During the first week of each month from February through June, the wetlands received water at an average rate of 2.8 m^3 min^{-1} (750 gpm, the flood pulse), and during the remainder of each month the flow rate averaged 0.57 m^3 min^{-1} (150 gpm). Problems with the pumps in January resulted in the flood pulse being delivered in the middle of that month. From July through December (low-flow months), the flow rate averaged 0.76 m^3 min^{-1} (200 gpm).

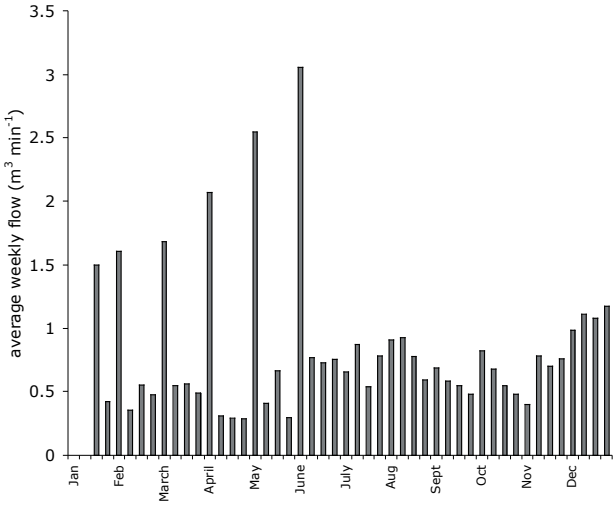

Figure 1. Hydroperiod of the experimental marshes in 2004. Each bar represents the average pumping rate for a one-week period.

Chamber design and placement

Non-steady-state gas sampling chambers (Klinger et al., 1994; Livingston and Hutchinson, 1995) were located in the edge-zones and in intermediate-depth areas ("marsh zones") of each wetland; these areas experienced intermittent inundation and periods of soil exposure. Six 0.27 m^2 circular HDPE bases were inserted permanently to 5-10 cm soil depth in these areas; permanent PVC frames to which

plastic-coated wires were attached for holding non-mercury thermometers were installed within the chamber bases. Fitted, 4-mil polyethylene bags with 3m Tygon vent tube (1.6 mm i.d.) and grey butyl rubber sampling ports were pulled over the permanent chamber frames at the time of sampling, and sealed around each chamber base with two 3 cm-wide elastic straps. Floating chambers made of the same materials and encircled by foam at the base for buoyancy were deployed in deeper, permanently inundated zones of each wetland (Figure 2). Bags were removed from permanent chamber frames at the end of each sampling period. Floating chambers and chambers in which emergent vegetation was removed measured 50 cm tall, while chambers containing emergent vegetation measured 150 cm tall. Chamber volume varied with the changing height of the water table. Permanently inundated areas contained only submerged and floating vegetation, while intermittently inundated areas included emergent macrophytes. Emergent macrophytes were continuously removed from half (n=4) of the chambers in the edge zones.

Gas Sampling

Gas sampling was carried out during 2004 over one diurnal cycle in February, over two diurnal cycles each month from March-October, and during the daytime only in November and December. Sampling was conducted during flood events and periods of low flow. Floating chambers were deployed beginning in July. Samples were taken in the morning (between 7-11 a.m.), afternoon (between 1-5 p.m.) and after dark (between 8 p.m. and 12 a.m) on diurnal sampling dates. The starting point (wetland and inflow/outflow) was chosen randomly on each date in order to avoid systematic bias due to changing intensities of solar radiation and soil temperature over sampling periods, which required approximately three hours to complete. Three to five samples were taken from the headspace of each chamber over a period of up to one hour during each sampling period (morning, afternoon, nighttime). Samples were extracted through septa with a 20-ml syringe with a one-way stopcock, and injected into pre-evacuated, 10-ml autosampler vials sealed with grey butyl septa. Vials were overfilled in order to minimize potential diffusion across the septa. Gas samples were stored at 4°C until analysis, and were analyzed within 7 days. Chamber temperature was recorded when each sample was extracted. Water level and temperature, soil temperature at five and ten cm depths, and percent cover of vegetation by species were recorded for each plot during each sampling period. Percent cover of vegetation (total and that of individual species) was estimated visually. Regressions between chamber water

Figure 2. Locations of gas-sampling chambers in the two experimental wetlands.

levels and wetland staff gage readings enabled calculation of negative water table depths for sampling periods in which the soil surface was exposed.

Analysis

Gas samples were analyzed on a Shimadzu GC-14A gas chromatograph equipped with a 40-position HT200H Autosampler, by flame ionization detection. A 1.8 m Porapak Q column was used for sample separation, and helium (25 ml min^{-1}) was the carrier gas (oven, injection and detector temperatures at 40°C, 40°C and 150°C respectively). Matheson methane standards, balanced with N_2, were used to perform 4-point calibration curves. Results were returned in parts per million (ppm), which were then converted to flux rates (mg CH_4-C m^{-2} h^{-1}), corrected for chamber volume and temperature (Healy et al., 1996). Regressions were performed on each flux rate in Microsoft Excel™ to determine linearity of flux. CH_4-C flux rates with correlations and $R^2 < 0.85$ were considered to be zero when individual measurements varied less than 1 ppm. If $R^2 < 0.85$ and CH_4 concentrations varied by more than 1 ppm over the sampling period, the flux rate was discarded. Therefore, only linear positive, negative or zero flux rates were used in the analyses; 90% of linear flux rates had $R^2 > 0.90$. Where removing one sample corrected a poor correlation to >0.90, the sample was eliminated from the calculation (Holland et al., 1999). This was reasonable given potential disturbances during attachment of the bag to the chamber frame at time zero, and to natural variability in flux rate, sometimes due to ebullition. In no case were fewer than three samples used for a concentration regression.

Flux rates were analyzed according to growing season (late April through September) and non-growing season, according to plot type (intermittently flooded with or without emergent macrophytes, permanently inundated), whether soil within plot types was inundated or exposed during sampling, and time of day (morning, afternoon, nighttime). Data were not normally distributed. Where log-transformation resulted in normal distributions, one-way analysis of variance (ANOVA) and t-tests were used to compare data sets; Mann-Whitney U and Wilcoxon Signed Ranks tests were used to compare flux rates where log transformation did not produce normal distributions. Analyses were performed in SPSS 11.0 (SPSS, 2004). To obtain an annual CH_4 budget, average CH_4-C fluxes from each chamber type for the growing and non-growing seasons were multiplied by 24 hours and the number of days in the season (158 and 208 respectively). Standard errors were obtained in the same way.

Results

Hydrology and Vegetation

Water levels in intermittently inundated chambers varied from <–20 to +39 cm, and in permanently inundated chambers from +1 to +41 cm deep. During low flow periods some of the chambers in intermittently flooded areas were inundated, and some had exposed soils, and certain marsh areas experienced more dramatic or frequent periods of drawdown due to small-scale variations in topography. The soil in intermittently flooded chambers was inundated or saturated during 66% of sampling occasions over the year, and 61% of sampling occasions during the growing season. Although the exaggerated flooding/low flow regime took place during the winter and spring, the relatively low flow conditions maintained during the growing season resulted in soils in the edge and upper marsh zones being periodically exposed when plant transpiration and minor fluctuations in the pumping rate facilitated lower water levels.

Plant species in permanently inundated areas included *Potamogeton nodosus* Poir., *P. pectinatus* L., *Ceratophyllum demersum* L., *Elodea Canadensis* Rich., and algal species. Emergent macrophyte species in pulsed chambers included *Schoenoplectus tabernaemontani* K.C. Gmel., *Leersia oryzoides* L. Sw., *Sparganium eurycarpum* Engelm., *Typha latifolia* L., *T. angustafolia* L., *Sagittaria latifolia* Willd., and *Eleocharis palustris* L. Pulsed chambers in which macrophytes were removed contained occasional *Lemna major* Meyer, *Ludwigia palustris* L., and algal species.

Methane Flux

Substantial methane fluxes were observed beginning in May, after the average soil temperature between 5-10 cm depths reached 15°C. Average growing-season rates of methane flux from intermittently flooded plots with and without emergent vegetation, 3.40 ± 0.37 and 3.54 ± 0.89 mg CH_4-C m^{-2} h^{-1} respectively, did not differ significantly

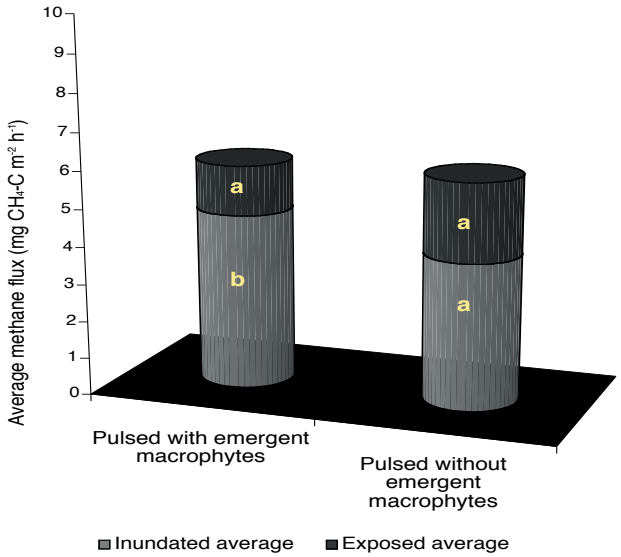

Figure 3. Average methane flux rates when soil in pulsed chambers was inundated vs. exposed during sampling Different letters indicate a significant difference in average methane flux rates between conditions. The number of samples is as follows: intermittently flooded with emergent macrophytes a) inundated n=114, b) exposed n=71; intermittently flooded without emergent macrophytes a) inundated n=70, b) exposed n=45.

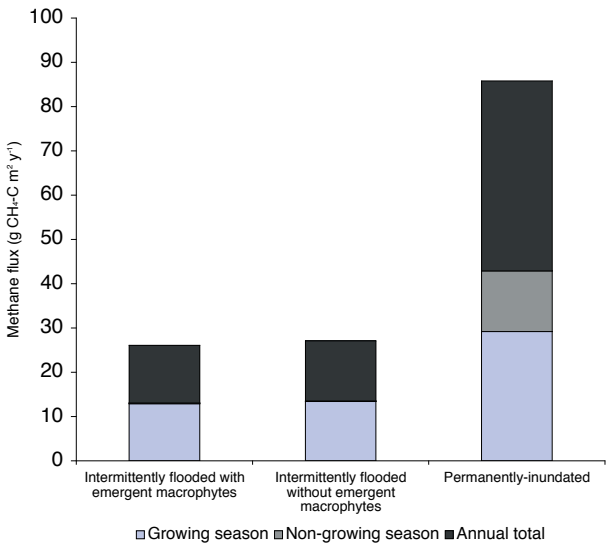

Figure 4. Seasonal and annual methane flux from the marshes for each wetland zone. Sample sizes are as follows: intermittently flooded with emergent macrophytes a) growing season n=185, b) non-growing season n=87; intermittently flooded without emergent macrophytes a) growing season n=115, b) non-growing season n=57; permanently inundated a) growing season n=111, b) non-growing season n=38.

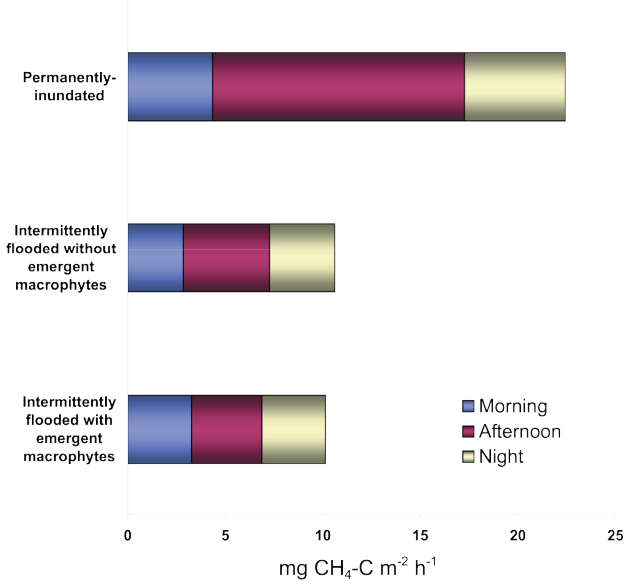

Figure 5. Average diurnal patterns in methane flux for each wetland zone in the growing season. The number of samples are as follows: intermittently flooded with emergent macrophytes a) morning n=59, b) afternoon n=61, c) night. n=65; intermittently flooded without emergent macrophytes a) morning n=36, b) afternoon n=37, c) night n=42; permanently-inundated a) morning n=35, b) afternoon n=38, 8 c) night n=38.

(p=0.398). During the growing season, intermittently flooded plots containing emergent macrophytes emitted, on average, 70% less methane when soil was exposed compared to when soil was inundated (1.32 ± 0.26 vs. 4.70 ± 0.54 mg CH_4-C m^{-2} h^{-1}), while those without emergent vegetation emitted 50% less methane when soil was exposed compared to when inundated (2.10 ± 0.92 vs. 3.93 ± 1.10 mg CH_4-C m^{-2} h^{-1}, Figure 3). The difference in methane emission during inundated and exposed conditions for intermittently flooded plots with macrophytes was significant (p=0.000) but presence or absence of water didn't result in a significant difference in methane flux in areas without emergent macrophytes (p = 0.082). During periods of inundation, methane emissions in intermittently flooded areas with and without macrophytes were significantly lower than emissions in permanently inundated areas (p=0.015 and p=0.000 respectively), where growing season fluxes averaged 7.8 ± 1.3 mg CH_4-C m^{-2} h^{-1}.

Methane fluxes from intermittently flooded areas virtually ceased by late September, but in permanently inundated areas methane continued to be emitted through November, when soils were approximately 12.5°C. Fluxes from permanently inundated areas during the non-growing season were comparable to growing season fluxes from intermittently flooded areas (Figure 4). Soil temperatures, averaged over all sampling periods, were 20.69 ± 0.34°C and 12.80 ± 0.11°C in October and November respectively in permanently inundated areas — approximately one degree higher than soil temperatures in intermittently flooded zones. Soils were exposed in 38% and 29% of pulsed chambers with and without emergent macrophytes, respectively, during October and November sampling periods.

Diurnal patterns in methane emission during the growing season were found in permanently inundated areas only, where afternoon flux rates were significantly higher than morning rates (p=0.004) and substantially higher than nighttime rates (p=0.06, Figure 5). The warmest soil temperatures occurred in the afternoon, averaging 3°C warmer than morning, and 1.2°C warmer than nighttime temperatures.

Discussion

Hydrology and Methane Flux

The finding that intermittently flooded wetland zones, when inundated, emitted significantly less methane than permanently inundated areas indicates a difference in soil conditions or microbial community structure and dynamics between these areas. Methanogenic communities may be more sensitive to changes in sediment redox status than methanotrophs (methane consuming microbes). In a study of relationships between methane dynamics and hydrology in a boreal bog, methane oxidation resumed less than a day after removal of anoxic conditions, while methanogenesis was not observed even two days after a return to anoxic conditions (Whalen and Reeburg, 2000). Periodic soil exposure may thus favor methanotrophic communities

over methanogens. Similar results were found in a study of effects of contrasting hydrologic treatments on methane flux from rice paddies in Louisiana, where periodic drawdowns of the water table reduced methane emissions by over 80% (Sass et al., 1992).

Concurrent studies of soil organic matter distribution in the experimental wetlands (Anderson et al., 2005) suggest that differences in methane flux among wetland zones is not due to contrasting concentrations of sediment organic carbon in intermittently and permanently inundated wetland zones. However, total accumulation of unconsolidated sediments is greater in permanently inundated areas than in edge zones and may result in greater availability of methanogenic substrates in continuously anoxic areas. In addition, the consistently low oxidation-reduction potential maintained under saturated conditions is a probable explanation for the greater methane production in permanently inundated areas; continuously low redox potential would facilitate uninterrupted metabolism of the methanogenic population, and maintain alternate electron acceptors such as Fe^{3+} in a depleted state. At higher redox potentials, use of substrates by competing microbial populations decreases substrate availability for methanogens (Segers, 1998), another probable cause of reduced methane flux from intermittently flooded wetland zones. Oxidation of labile C during periods of soil exposure could lessen available substrates as well.

Emergent Macrophytes and Methane Flux

Methane flux is highest at midday if pressurized convection of the gas through plant tissue is occurring, due to heat and humidity-induced pressure differentials between plant tissues and the atmosphere (Schütz et al., 1991). The lack of diurnal variation in chambers containing emergent macrophytes supports an interpretation that pressurized convection of CH_4 through plant tissue was not the dominant pathway for release of the gas, although this mechanism has been demonstrated for genera present in our study (*Typha*, *Sparganium* and *Eleocharis*) (Brix et al., 1992; Vretare Strand, 2002). The greater average reduction in CH_4 flux during drawdown in areas containing macrophytes, compared to areas without emergent vegetation, may be attributed in part to aeration of the soil due to transport of oxygen to the rhizosphere via aerenchyma.

The variable of ultimate importance in this study was whether plots had been subjected to fluctuating hydrologic conditions, not whether emergent macrophytes were present. These findings are not consistent with frequently demonstrated correlations between primary productivity and methane emission in wetlands (Whalen, 2005). During this study, soils in periodically flooded chambers remained exposed for up to two weeks between flood pulses, and intermittently during the low-flow period from July to December. Primary productivity may be strongly related to CH_4 flux in wetlands with constant positive water tables (Whiting and Chanton, 1993), but in our study of pulsed water levels, duration of flooding was much more important.

Comparison with Other Studies

Our flux rates (3.4 – 7.7 mg m^{-2} h^{-1} during the growing season) fall within the range reported for natural wetlands in which methane flux was assessed using non-steady-state chambers. Comprehensive studies of methane flux rates from floodplains and littoral wetlands across a variety of climates report average growing season fluxes of 1.3 to 15 mg CH_4-C m^{-2} h^{-1} in permanently inundated areas, and -0.23 to 6 mg CH_4-C m^{-2} h^{-1} in periodically-flooded (pulsed) areas (Devol et al., 1988; Pulliam, 1993; Juutinen et al., 2001). Higher flux rates occur during waterlogged conditions than during extended drawdowns across wetland ecosystems (Harris et al., 1982, Smith et al., 2000). Annual flux rates of 35 g CH_4-C m^{-2} y^{-1} are reported for forested swamps and marshes at similar latitudes (Bartlett and Harris, 1993). Our rates, 13 to 43 g CH_4-C m^{-2} y^{-1} for pulsed and non-pulsed areas respectively, fall within this range, indicating that after one decade of development created riparian wetlands compare to natural ecosystems in this function.

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